Seismic hazard analysis for a bridge across Marikina River with consideration of near-fault effects

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ABSTRACT

The Valley Fault System in Metro Manila, Philippines is widely considered to be an impending threat in releasing a large-scale earthquake. Such an earthquake is forecasted to impose severe casualties and economic losses to the business center of the country. Thus, the importance of a resilient road network, even during disasters, cannot be overstated. In this paper, a site-specific Seismic Hazard Analysis for a bridge across Marikina River was carried out to develop two sets of ground motion intensity levels (return periods of 100 and 1,000 years), with each corresponding to a desired seismic performance level. Both deterministic and probabilistic approaches were carried out to develop the site-specific uniform hazard spectrum. Spectral ordinates were then modified *a posteriori* to account for near-fault effects and resolve to fault-normal and fault-parallel components. Pursuant to local bridge design standards, the site-specific results were compared with the code-prescribed design response spectra to obtain the final envelope. The final envelope response spectrum was further utilized as the target for modifying recorded time-histories with similar seismological characteristics. The modification process greatly reduced the variability across the period range significant for the bridge structure. Despite this, the earthquake time-histories developed in this study therefore provided a reliable representation of seismic hazard for nonlinear dynamic analysis.

1 INTRODUCTION

In the Philippines, infrastructure construction and development has been on quite the rise over the past few years as part of the government's "*Build! Build! Build!*" Program which was launched in 2017. One of the main objectives of this program is to alleviate traffic congestion in heavily populated areas such as Metro Manila, Philippines. The Valley Fault System (VFS) is widely considered to be an impending threat in releasing a large-scale earthquake. Such an earthquake is forecasted to impose severe casualties and economic losses on the business center of the country. Thus, the importance of a resilient road network, even during disasters, cannot be overstated.

In this paper, a site-specific Seismic Hazard Analysis (SHA) study for a proposed extradosed pre-stressed concrete box girder bridge in Marikina River was carried out—knowing fully well that the manifestation of near-fault effects is to be expected due to the proximity of the active VFS.

2 GEOLOGIC CONSIDERATIONS

2.1 Regional and site geology

The site is located near the borderline between the Late Pliocene to Early Pleistocene Guadalupe Tuff Formation (GTF or GF) and Holocene/Quaternary Alluvium (QAl) deposits, as shown below in the map (Fig. 1) published by the Mines and Geosciences Bureau (MGB). Moreover, the site geology is primarily dominated by the GTF—the regional bedrock of Metro Manila, but is mantled by a residual soil cover of varying thickness. The GTF is characterized as very soft, highly weathered, sandstones and siltstones with traces of hard/very dense soil.

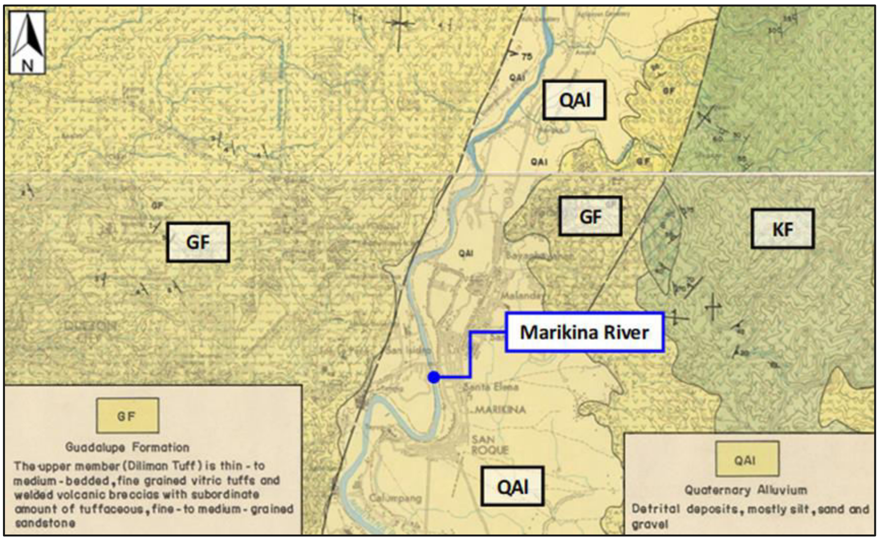
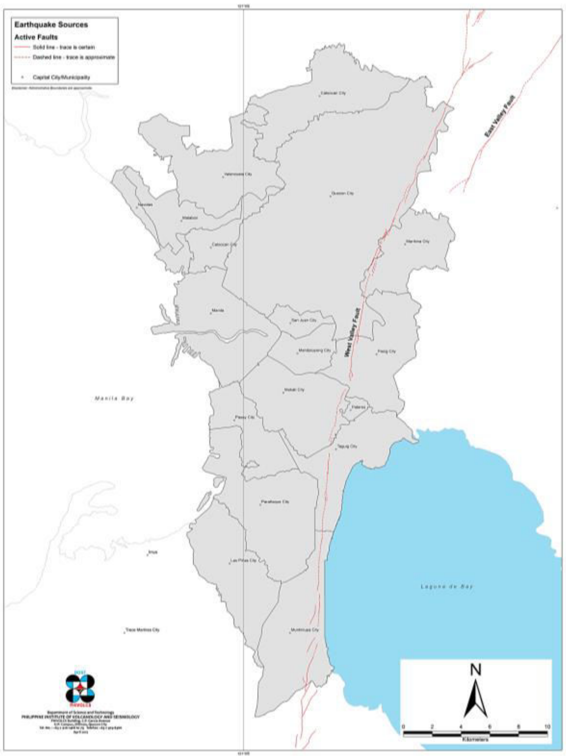


Figure 1: Stitched 1:50,000-scale Geologic Maps of the Montalban Quadrangle and the Manila and Quezon City Quadrangle (Modified from MGB, 1983)

2.2 Tectonic setting and faulting

The seismicity of the Philippines can be explained in terms of its tectonic framework. The Philippines may be subdivided into the Philippine Mobile Belt and Palawan (Seismic Zones 4 and 2, respectively). Metro Manila is located within the Philippine Mobile Belt. The Philippine Mobile Belt refers to the portion of the Philippine archipelago bounded in the west by the Manila, Negros, and Cotabato Trenches, and in the east by the East Luzon Trough and Philippine Trench. Moreover, the active Valley Fault System (VFS), consisting of the West and East Valley Faults, cuts through the greater Metro Manila, as shown in the map (Fig. 2) published by the Philippine Institute of Volcanology and Seismology (PHIVOLCS), and is therefore the most critical fault (system) for the development.

The West Valley Fault (WVF) extends from the southern Sierra Madre to Tagaytay over a distance of 110 km. The well-defined, east-facing escarpment separates the Guadalupe Diliman Plateau from the Marikina Valley. On the other hand, the shorter East Valley Fault (EVF) extends over a distance of about 30 km. The prominent, west-facing escarpment observed in the San Mateo-Marikina-Antipolo area separates the Antipolo Plateau from the Marikina Valley.



The VFS is said to have a recurrence interval of 200 to 400 years during [illegible] years, as identified by Daligdig et al. (1997) based on Carbon-14 dating. The same study has th[illegible] occurring during the 18th or 19th century. M[illegible]ere is no seismic activity that can be related to the VFS. Nevertheless, several lines of evidence indicate that the faults a[illegible]ctive, such as (1) morphologi[illegible]res; (2) the presence of fault planes in the Quaternary Diliman Tuff; (3) the presence of sag ponds; (4) deformation in alluvial material in trenches excavated during paleoseismic studies; and (5) Carbon-14 dating data.

East Valley Fault
Marikina Valley
Antipolo Plateau
Guadalupe Diliman Plateau

Despite not being associated with any seismic activity over the last couple of centuries, the VFS is shown to still be geo[illegible]ve as PHIVOLCS continuously monitors it[illegible]his is referred to, locally, as a "*seismic gap*." Risk from seismic gaps can be higher despite the absence of seismic activity because stress is continuously accumulating—making them candidates for major earthquakes.

West Valley Fault

Figure 2: Distribution of active faults in Metro Manila (PHIVOLCS, 2015)

3 SITE CHARACTERIZATION

The geotechnical investigation program for the bridge comprised of drilling 13 boreholes. To supplement the investigation program, five P-S Suspension Logging (PSL) tests were conducted along the bridge alignment (both onshore and offshore). The PSL is a downhole geophysical test that measures in-situ shear wave velocity (V_s) and compressional wave velocity (V_p) by depth. By obtaining V_s and V_p data, not only can the site class be determined per local building codes, but the V_s data will also be utilized in characterizing the effects of shallow subsurface stiffness on ground motions in site-specific hazard calculations.

The PSL results indicate that the representative 30-meter shear wave velocity (V_{s30}) of the site ranges from 222.74 m/s to 292.46 m/s. However, there are plans of excavating the upper 4 to 5 m of loose material as part of the foundation preparation works. Removing the loose upper layers in the calculation, the V_{s30} values were re-evaluated and determined to be 350 m/s on average. With this representative value, the site subsurface was categorized under Site Class S_C, which is described as very dense soil and/or soft rock. This V_{s30} value shall further be utilized in succeeding calculations and in the development of ground motions.

4 SEISMIC HAZARD ANALYSIS

Seismic Hazard Analysis is the process of quantifying the expected earthquake-induced ground shaking on-site. There are two methods of performing SHA: (1) a deterministic scenario-based approach (DSHA); or (2) a probabilistic approach (PSHA). The latter is carried out primarily to obtain the shaking hazard/seismic demand at different return periods (or recurrence intervals), and is therefore necessary if Performance-Based Design (PBD) principles will be employed.

In the context of PBD, the 2013 Department of Public Works and Highways (DPWH) Bridge Seismic Design Specifications (BSDS) require serviceability (immediate operation) and collapse prevention performance objectives. The ground motion levels associated with these performance objectives have return periods of 100 years (53% probability of exceedance in 75 years) and 1,000 years (7% probability of exceedance in 75 years). The 100-year hazard level will be referred to as the Level 1 Earthquake (L1), whereas the 1,000-year hazard level will be the Level 2 Earthquake (L2).

4.1 Ground motion prediction equations

Attenuation models for active shallow crustal (ASC) events were developed through collaborative effort and were released by the Pacific Earthquake Engineering Research Center (PEER) in 2008 under the NGA-West project, and subsequently updated and improved under the NGA-West2 project in 2014. Four of these ground motion prediction equations (GMPE) are:

- Abrahamson, Silva, and Kamai (2013)
- Boore, Stewart, Seyhan, and Atkinson (2013)
- Campbell and Bozorgnia (2013)
- Chiou and Youngs (2013)

For subduction zone (SZ) sources, the updated BC Hydro (Abrahamson et al., 2018), Parker et al. (2020), Zhao et al. (2016), Atkinson and Boore (2003), and Garcia et al. (2005) are also adopted.

4.2 Near-fault effects

The nature of ground shaking for some locations within a few kilometers of an active fault can be different from more distant sites. For such locations, near-fault effects (NFE) are apparent, and should thus be investigated when characterizing ground motions. NFEs result in an overall increase of the seismic hazard and are said to manifest in three ways: (1) rupture directivity effects; (2) distinctive ground motion directionality; (3) fling-step effects.

As discussed in Section 2.2, the trace/escarpment of the WVF forms the western boundary of the Marikina Valley. Located within the segment of the Marikina River near the northwestern boundary of Marikina, the site is only about 300 m east of the WVF (and 4 km west of the EVF). As such, NFEs will be accounted for in the development of the design ground motions, and shall be applied to the calculated intensity measures *a posteriori* (i.e. applied post-calculation).

4.2.1 Ground motion directionality

In seismic analysis, structural systems are subjected to two-component horizontal ground motions recorded at orthogonal directions. Due to the generally random nature of horizontal ground shaking, these orthogonal ground motions are just typically aligned to the longitudinal and transverse axes of the structure. However, the maximum structural response may not necessarily occur along the structure's longitudinal and transverse axes—it in fact may occur directed along some other arbitrary orientation. The distinctive difference in intensity in one orientation than in other directions is referred to as the polarization, or "*directionality*," of the ground motion. The Shahi and Baker (2014) model is used to derive the maximum-direction component from the median intensity measures.

4.2.2 Rupture directivity

The term "*directivity*" is associated with all factors that can cause ground motion amplification, such as strong velocity pulses or polarization of ground shaking. Earlier directivity model provides amplification factors to modify the median response spectra from typical ground motion models to account for rupture directivity effects in the fault-normal (FN), fault-parallel (FP), or average-directivity components. In this study, the FN and FP directivity factors are developed using the Bayless and Somerville (2013) model.

4.2.3 Fling-step effects

Fling-steps are large permanent ground displacements caused by the sudden release of stress and displacement that have slowly accumulated in the earth's crust over long periods of time (Burks and Baker, 2016). Fling-steps are characterized by a step or jump in the FP component displacement time-histories of strike-slip faults (such as the VFS). Fling-steps, in this study, are reconstructed and integrated into developed time-history FP components using the Kamai et al. (2014) model.

4.3 Deterministic seismic hazard analysis

DSHA aims to quantify the effects of the ground motion intensity at a particular site based on a predefined scenario earthquake. Understanding that the VFS is the most critical earthquake generator for the site, DSHA was performed considering hypothetical rupture scenarios from both the WVF and EVF using the aforementioned GMPEs for ASC events in equal weights (25% each). Compliant with DPWH BSDS 2013 Article 3.4.2 Item 5, the maximum envelope of the median (i.e. 50th percentile) earthquake scenarios considered will be taken as the final DSHA spectrum.

4.4 Probabilistic seismic hazard analysis

In performing PSHA, all possible earthquake events, with their corresponding probabilities of occurrence, from multiple sources are considered, to obtain a full distribution of ground shaking intensity levels based on specific rates of exceedance (Baker 2015). The plot of the intensity, which may be represented by the spectral acceleration, against the rate of exceedance is typically called a hazard curve. Spectral acceleration ordinates at varying oscillator periods from different hazard curves at a target rate of exceedance can be combined to form a uniform hazard spectrum. The principle of PSHA works based on the Total Probability Theorem. Moreover, PSHA calculations deal with predefined earthquake generators and seismicity data from which magnitude-recurrence relationships for each source are computed. The magnitude-recurrence relationship for earthquakes can be defined by the Gutenberg-Richter (GR) recurrence law:

$$log(N) = a - bm \tag{1}$$

where N = rate of earthquakes with magnitudes greater than m; a = activity rate per source; and b = relative ratio of small and large magnitudes per source. The PSHA model is analyzed using the OpenQuake Engine (ver. 3.11.3) developed by the Global Earthquake Model (GEM) Foundation. A logic tree is implemented to account for epistemic uncertainties in the GMPEs and other model techniques. To address the uncertainties related to GR parameters, additional branches for M_{max} and b values are also implemented in the logic tree.

4.5 Seismicity data

As part of the PSHA process, seismicity data from 1619 to August 2021 were gathered from the United States Geological Survey (USGS) catalog, the extended GEM earthquake database, as well as the Global Historical Earthquake Catalogue compiled by Albini et al. (2014), and merged as one complete earthquake catalog (redundant events removed). All in all, this catalog contains 14,829 earthquake events whose magnitudes are 4.5 and higher. These events in this catalog, however, are of different magnitude types, and can also be either foreshocks or aftershocks. In order for the catalog to be useable in PSHA calculations, the following pre-processing steps shall be carried out:

1. Homogenization of different magnitude types to moment magnitude (M_w) scale
2. Event declustering or aftershock filtering (from the original 14,829 earthquake events, only 4,159 main shocks were identified)
3. Catalog completeness is employed to minimize probabilistic bias

4.6 Source models

General area seismic sources were defined based on the assumed seismotectonic boundaries (within 320 to 450 km of the site), and the identified patterns and clustering of earthquakes in the earthquake catalog.

Previous PSHA works published in literature, such as from Peñarubia et al. (2017), were also reviewed for area source modeling. As presented in Figure 3, these zones are grouped into three depth categories: shallow (0 to 50 km depth range), mid-depth (50 to 100 km depth range), and deep (deeper than 100 km).

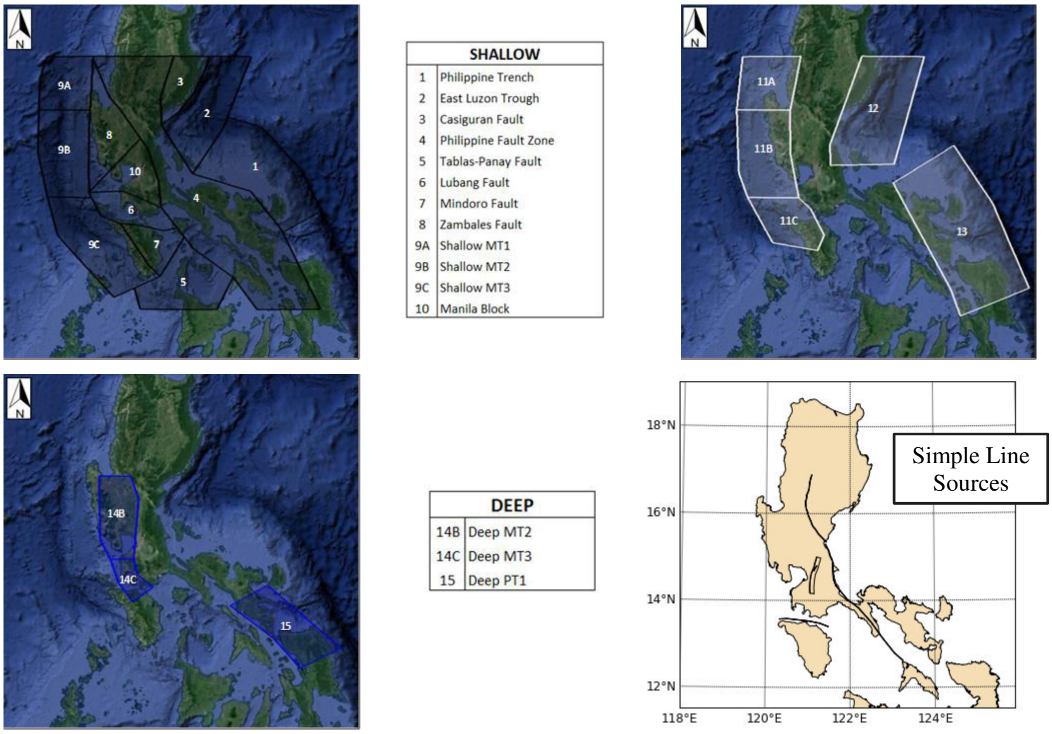


Figure 3: General area source and simple line source models

Furthermore, seismic sources were also modeled as simple line sources, which utilizes annual slip rates, instead of seismic event count, to calculate activity rate and the corresponding magnitude-frequency distribution (MFD). In other words, Equation 1 (GR recurrence law) is not utilized in line source modelling. Modeling line sources is particularly crucial for active earthquake generators whose seismic activity distributions are sparse, such as the VFS (as mentioned in Section 2.2). The simple line sources considered in this study are also shown in Figure 3. The slip rates of the considered seismic sources were compiled from previous works, such as from Peñarubia et al. (2020).

4.7 Response spectra

The following figures show the L1 and L2 response spectra developed from site-specific DSHA and PSHA calculations. In compliance with DPWH BSDS 2013 Article 3.4.2 Item 6, the results from the two methods shall be compared with the code-prescribed design response spectra to obtain the final envelope.

Figure 4 shows that the 100-year PSHA spectrum governed over the code's lower limit (two-thirds of the code-prescribed spectrum). Moreover, NFEs are neglected at the service level due to the low intensity levels associated with the short return period. On the other hand, the top image of Figure 5 shows that the DSHA spectrum is higher than its probabilistic counterpart within the long-period region. However, DPWH BSDS 2013 does not necessarily require the consideration of DSHA ground motions, so it was ultimately decided to neglect the DSHA spectrum. In any case, like the L1 spectrum, the final L2 envelope is also governed by the PSHA spectrum as it is also higher than the code's lower limit at that level. Finally, as discussed in Section 4.2, NFEs are applied—resulting in the amplified spectra, decomposed into the FN and FP components, shown in the bottom image of Figure 5.

Table 1: Ordinates of site-specific response spectra.

Period, T (s)	Spectral Acceleration, S_a (g)		
	L1	L2 FN	L2 FP
0	0.358	0.729	0.729
0.075	0.623	1.381	1.381
0.10	0.712	1.568	1.568
0.15	0.791	1.694	1.694
0.20	0.816	1.705	1.705
0.25	0.801	1.668	1.668
0.30	0.755	1.577	1.577
0.40	0.651	1.402	1.402
0.50	0.558	1.240	1.240
0.75	0.395	1.034	0.931
1.0	0.282	0.807	0.708
1.5	0.157	0.484	0.393
2.0	0.101	0.337	0.250
3.0	0.062	0.199	0.147
4.0	0.033	0.124	0.090
5.0	0.023	0.090	0.063
7.5	0.012	0.047	0.032
10.0	0.007	0.030	0.020

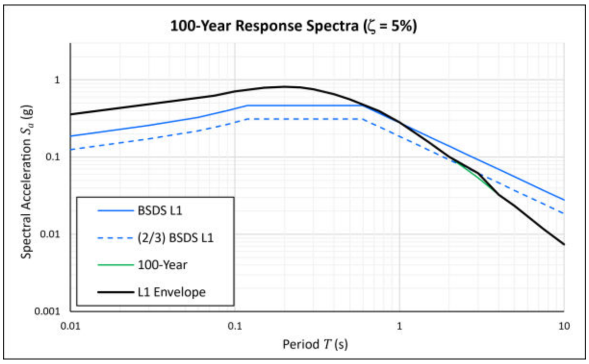
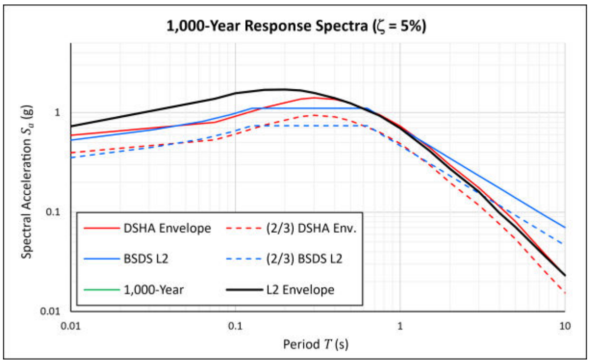


Figure 4: Site-specific L1 response spectrum



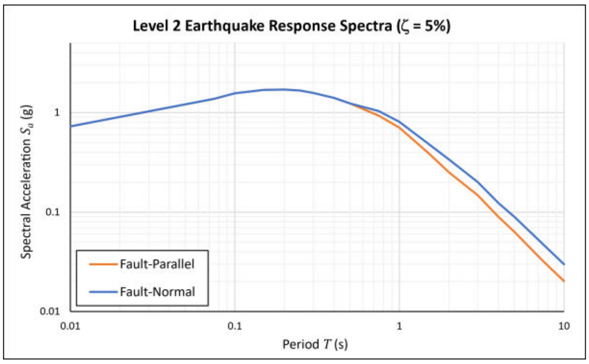


Figure 5: Site-specific L2 response spectra: no NFE (top) and with NFE (bottom)

4.8 Ground motion (time-history) modification

Careful consideration is applied in selecting empirical seed ground motion time-histories such as seismological features, local site conditions at the recording station, and the like. When applicable, near-fault effects must also be accounted for and maintained after modification. The unmodified (seed) ground motion acceleration time-histories were obtained from the PEER NGA-West2 Ground Motion Database. Spectral matching, the process of modifying the amplitude and/or frequency content of ground motions to match the expected hazard on-site, was carried out for both ground motion levels using SeismoMatch (Seismosoft 2021).

Ultimately, the matching assessment was done by evaluating the amplitude compatibility of the maximum-direction spectra of the matched time-histories to the target spectra over a period range of interest (1 to 4 seconds) provided by the bridge designer. Finally, fling-steps, based on the characteristics of the WVF, are reconstructed and integrated into the FP components as discussed in Section 4.2.3.

5 CONCLUSIONS

For large infrastructure projects in high-seismicity areas like the Philippines, it is always important to consider positioning and orientation of the structure because ground motion directionality and NFEs can be detrimental. In this study, a site-specific SHA exercise (following standard procedures) was conducted, with NFEs in mind, for a proposed bridge located just about 300 m away from an active seismic source. By going through the rigorous process of conducting site-specific analysis, seismic design loads are more realistic and will oftentimes lead to design optimization (over typically conservative code-prescribed loads) without compromising the resiliency and safety of the structure. In fact, the site-specific SHA exercise in this case even led to a safer, more appropriate consideration of additional amplification effects because, unfortunately, the local bridge design code of the Philippines (DPWH BSDS 2013) does not provide any set of provisions to consider additional NFEs (explicitly mentioned). The ground motion developed in this study are therefore a reliable representation of on-site seismic hazard.

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